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Industrial Electrical Engineering and Automation

Condition Based Maintenance - Submarine A26

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[Condition Based Maintenance – Submarine A26]

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ABSTRACT

This project is a study that has described what condition based maintenance is and has examined the possibilities with condition based maintenance on the new A26 submarine. It finishes with a detailed case study of how a condition based maintenance system could look like on the submarine's diesel engines.

Questions that have been answered are; what is condition based maintenance and how does it work? What are the possibilities to install a condition based maintenance system on the new A26 submarine? What has to be considered? What exists on the A26 submarine already that can be used and what has to be added for such a system to work properly?

Condition based maintenance is a maintenance strategy that aims to optimize the overall maintenance plan. This is done by analyzing the machine health by making different kinds of measurements on the machine, e.g. vibration measurements, thermography, ultrasonic measurements, oil analysis etc. The measured values are then analyzed either by an advanced software program or a technician that can determine when the machine will break down and plan the correct maintenance action at the optimal time. To be able to do this one need to know what the expected levels are for the measured property for the current run mode, what the critical levels are, and how various errors develop.

On board the A26 there is a Ship Control and Monitoring System (SCMS) which is a system for controlling and monitoring everything on the ship. This system, with its I/O-modules spread out throughout the ship, can be used to a great advantage. It is relatively easy to add new sensors to it and store measured data on board the ship. This makes a permanently installed system very appealing, although some systems might benefit from a round based system.

To analyze all the acquired data an analysis program should be installed on the SCMS. If this program should be developed internally at Kockums or if it should be bought from an external supplier still needs further investigations.

A detailed study of what a condition based maintenance system could look like has been made on the diesel engines. On a Scania marine diesel engine there are already a lot of sensors that monitor useful information. However, that information is not considered enough to make a complete satisfactory machine health diagnosis. To be able to pinpoint most possible failures it has been found that vibration monitoring combined with oil analysis with a permanently installed system is probably the best solution. For that, sensors monitoring vibrations and oil condition need to be added.

SAMMANFATTNING

Det här projektet är en studie som har definierat vad tillståndsbaserat underhåll är samt undersökt möjligheterna med tillståndsbaserat underhåll på nya ubåt A26. Det avslutas med en detaljerad fallstudie om hur ett tillståndsbaserat underhållssystem kan se ut på ubåtens dieselmotorer.

Frågor som har besvarats är; vad är tillståndsbaserat underhåll och hur fungerar det? Vad finns det för möjligheter att införa ett tillståndsbaserat underhållssystem på nya ubåt A26? Vad måste övervägas? Vad finns på ubåt A26 redan som kan användas och vad måste läggas till för att ett sådant system ska fungera tillfredsställande?

Tillståndsbaserat underhåll är en underhållsstrategi som strävar efter att optimera den generella underhållsplanen. Detta görs genom att analysera maskinhälsan genom att göra olika sorters mätningar på maskinen, till exempel vibrationsmätningar, termografi, ultraljudsmätningar, oljeanalyser etc. De uppmätta värdena analyseras sedan antingen av ett avancerat mjukvaruprogram eller en tekniker som kan fastställa när maskinen kommer gå sönder och planera korrekt underhållsåtgärd vid optimal tidpunkt. För att kunna göra detta måste man veta vad de förväntade värdena ska vara för den uppmätta storheten vid tillfälligt körläge, vad de kritiska nivåerna är, samt hur olika maskinfel utvecklas med tiden.

Ombord ubåt A26 finns ett så kallat "Ship Control and Monitoring System" (SCMS), vilket är ett system för att kontrollera och övervaka allting i båten. Detta system, med dess I/O-moduler utspridda över hela båten, kan användas med stora fördelar. Det är relativt enkelt att lägga till nya sensorer till systemet och lagra undan uppmätt data ombord. Detta gör att ett permanentinstallerat tillståndsbaserat underhållssystem är väldigt tilltalande, dock kan det vara fördelaktigt att använda sig av ett rondbaserat system på vissa system.

För att kunna analysera insamlad data borde ett analysprogram installeras på SCMS. Om detta program ska utvecklas internt på Kockums eller om det ska köpas in av en extern leverantör måste fortfarande utvärderas.

En detaljerad studie på hur ett tillståndsbaserat underhållssystem kan se ut har gjorts på dieselmotorerna. På en Scania marindieselmotor finns det redan ett flertal sensorer som övervakar användbar information. Denna information är dock inte tillräcklig för att göra en fullständig maskinhälsodiagnos. För att kunna fastställa och precisera de vanligaste maskinfelen har man funnit att vibrationsövervakning kombinerat med oljeanalys med ett permanentinstallerat system är den troligtvis bästa lösningen. För detta krävs att sensorer för vibrationsövervakning och oljeanalyser läggs till.

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PREFACE

This Master's thesis was carried out at Kockums AB in Malmö in cooperation with the *Division of Industrial Electrical Engineering and Automation* at the Faculty of Engineering at Lund University during spring and summer 2012.

This thesis was conducted due to a demand from the Swedish Defence Materiel Administration (försvarets materialverk – FMV) that condition based monitoring for the next generation of submarines was to be investigated. The object was to examine the possibilities of implementing condition based monitoring on the new A26 submarine that is under development at Kockums AB and to come up with suggestions of how/if it can be done.

This thesis work has been a great learning experience for me. Due to the fact that maintenance is involved in all the different systems on board a submarine, I have had to build up an understanding of the whole submarine and all of its subsystems. I have had to deal with problems throughout the project that I did not expect and I have developed my ability to work around obstacles and deal with unexpected problems. An example of this is confidentiality. Due to the fact that the Swedish Armed Forces are involved and some information may be a matter of national security, some information could be hard to obtain. Other kinds of information could also be protected by the company as secret corporate information due to patent protection etc. An example where this problem was prominent is the detailed case study that initially was planned to be made on the Stirling engine. This could not be done however due to the fact that the information needed was protected by confidentiality. So at the last minute I had to change plans and make the case study on the diesel engines instead.

It is assumed that the reader of this thesis possesses basic knowledge in mechanical and electrical engineering.

Lund September 2012

Johan Schantz

NOMENCLATURE

A	System availability

ABBREVIATIONS

AIP	Air independent propulsion
ANN	Artificial neural network
ASW	Anti submarine warfare
CBM	Condition based maintenance
CM	Corrective maintenance
FMV	Försvarets materialverk
GOX	Gaseous oxygen
KAB	Kockums AB
LOX	Liquid oxygen
PIS	Permanently installed system
PM	Preventive maintenance
RPM	Revolutions per minute
SCMS	Ship control and monitoring system
SM	Scheduled maintenance
SRV	Submarine rescue vehicle
TLS	Through life support

1 INTRODUCTION

1.1 COMPANY HISTORY

Kockums AB (KAB) stands for leading-edge, world-class naval technology – both above and below the surface. They design, build and maintain naval surface vessels and submarines that incorporate the most advanced stealth technology. They are also active in a number of specialized fields, such as mine clearance and submarine rescue systems. Operations are based in Sweden in Malmö, at Muskö and in Karlskrona [1].

Kockums in Malmö developed out of the engineering works established by Frans Henrik Kockum in 1840. In the 1870s, Kockums became a shipyard, and in 1875 delivered its first vessel to the Swedish Navy, the steam-crane barge Torpedo. 39 years later, in 1914, the first submarines were launched; Svärdfisken and Tumlaren (Swordfish and Porpoise). In the 1950s, Kockums was a very large shipyard that delivered the world's highest tonnage of merchant shipping. Today, the shipyard in Malmö is shut down and the Malmö facility is focused on the design of submarines and the Stirling Air Independent Propulsion (AIP) system, as well as other research and development [1].

Karlskronavarvet (Karlskrona Shipyard) started operations as early as 1679, when King Karl XI gave orders to establish a naval base and shipyard in southern Sweden. Over the years, the shipyard has built ships both of oak and steel, but the preferred material for the stealth technology built into today's new generation of naval vessels is carbon fiber (surface vessels only). In 1998, Kockums in Malmö and Karlskronavarvet were combined to form a single company, Kockums AB. In conjunction with this merger, a decision was taken to concentrate all ship production to Karlskrona. Kockums AB is now part of ThyssenKrupp Marine Systems [1].

1.2 SUBMARINES

A submarine is defined as a naval vessel that can operate under the surface of the water. It should be able to solve tasks in all kinds of conflict levels; peace, crisis, neutrality or war, and it should be able to do so without being detected and with a low risk-taking. It should be able to operate for a long period of time and behave autonomously, and if needed, be able to pose a great threat to enemies [2].

Submarines can be divided into two categories, civil and military. Civil submarines are usually some kind of research vessels or commercial entertainment submarines. Military submarines can be divided into three classes; nuclear submarines, conventional submarines and special submarines [2], see Figure 1.1.

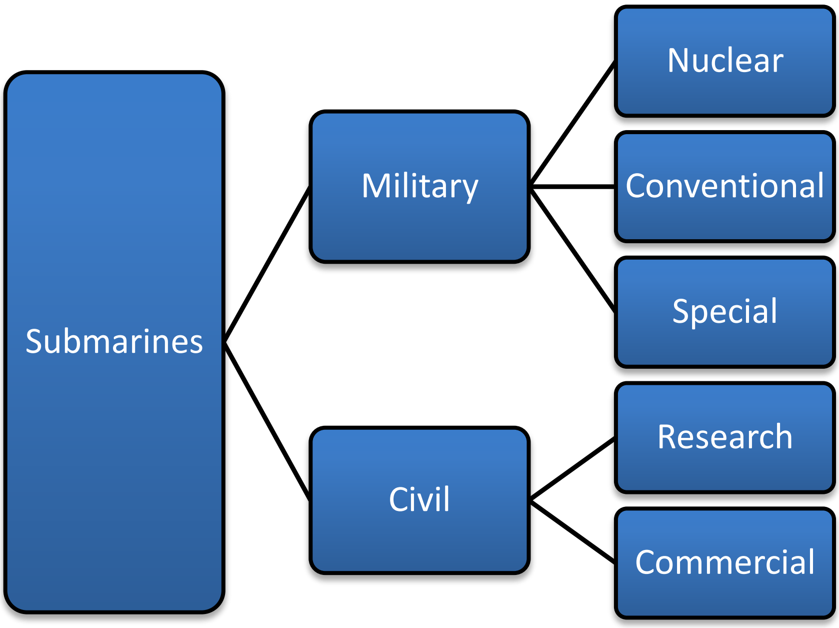

Figure 1.1 Classification of submarines.

1.2.1 MILITARY SUBMARINES

A nuclear submarine has a nuclear reactor on board which is capable of supplying the submarine with large amounts of energy. This means that the submarine does not have any high demands on energy saving systems and that it can operate and stay submerged for a very long time compared to conventional submarines.

Conventional submarines, which is the kind of submarines that KAB has been building for nearly a century now, do not have a nuclear reactor on board and usually uses diesel-electric power systems instead. This means that the submarines have a higher demand on energy saving systems since the diesel-electric power system does not supply as much energy as a nuclear reactor. However, conventional submarines are much quieter when submerged which can sometimes be a great advantage. Some modern conventional submarines also use AIP systems, e.g. the Swedish Gotland class submarine which uses the Stirling AIP system.

Special submarines are usually smaller submarines built for special purposes such as the Kockums-built Submarine Rescue Vehicle (SRV), see Figure 1.2.

Figure 1.2 KAB's Submarine Rescue Vehicle (source: [3]).

1.2.2 KOCKUMS AB SUBMARINES

KAB has developed and built conventional submarines for nearly a century and for the past 50 years (approximately) been building modern submarines. With modern submarines means streamline shaped submarines intended to stay and act submerged, unlike the earlier ships that were shaped and acted like surface vessels that were able to dive. All the submarines of modern type are presented in Table 1.1.

Table 1.1 Kockums submarines of modern type (source: [2]).

Name	Type	Launched year
Sjöormen	A11	1967-68
Näcken	A14	1978-79
Västergötland	A17	1986-88
Gotland (AIP)	A19	1997-98
Södermanland	Västergötland + AIP	2005
A26	A26	Under development, planned for 2018

1.2.3 THE GOTLAND CLASS SUBMARINE

The A19 Gotland Class is one of the world's most modern conventional submarines. It is designed to be able to accomplish all kinds of possible submarine missions such as anti-shipping operations, anti submarine warfare (ASW) missions, surveillance, special operations and mine-laying tasks. The Gotland Class is the first submarine class in operation with an air independent propulsion system; the Stirling AIP system. This combined with other unique features including overall low signatures, extreme shock resistance and a powerful combat system, provides the ultimate solution in non-nuclear submarine technology [4].

The Gotland Class submarine is 60 meters long, 6.2 meters wide and has a displacement of 1500 tons. It has the capability to stay submerged for several weeks and can be operated with a crew of only 25 thanks to the use of automation and remote control. Three submarines of the Gotland class, HMS Gotland, HMS Uppland and HMS Halland are now in service with the Royal Swedish Navy [4].

A new improved generation of submarines, the Kockums A26, is currently under development at KAB for the Royal Swedish Navy.

1.2.4 KOCKUMS STIRLING AIP SYSTEM

The Stirling AIP system, used in both the Gotland class and the Södermanland class submarines, is a product of Kockums. It is based on a Stirling engine, which is a heat engine with an external combustion chamber that converts the generated heat into mechanical work. The heat can be generated from any kind of fuel; oil, diesel, petrol or gas, which makes it very flexible. It is also very silent, virtually vibration free and very clean due to the external combustion, which makes it ideal for submarine use [5].

The Kockums Stirling AIP system uses diesel fuel and gaseous oxygen (GOX) for the combustion. The GOX is produced by vaporizing liquid oxygen (LOX) that is stored in cryogenic tanks on board the ship. The generated mechanical work is then converted to electrical energy for use in the submarine. This extra energy, which can be obtained without air supply, can extend the submerged endurance of conventional submarines from a few days up to several weeks, and thus outperform any other conventional submarine. This is achieved by less frequent requirements for noisy battery recharging with the diesel generators. The principle of the Stirling AIP system is shown in Figure 1.3.

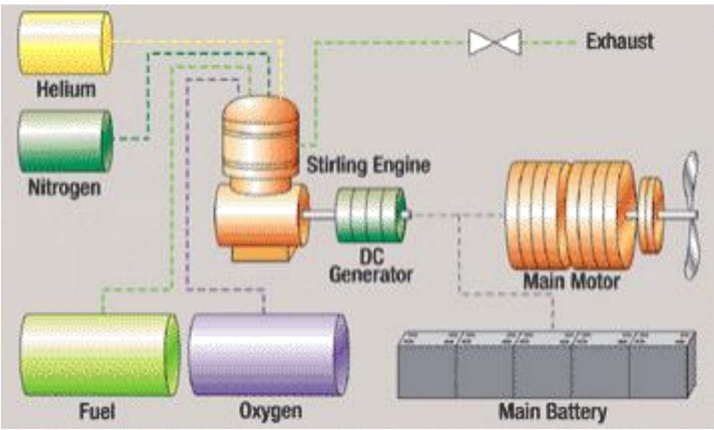

Figure 1.3 The principle of the Stirling AIP system (source: [5]).

The Stirling AIP system is an add-on system, which means that a submarine is never dependent on it and when the LOX supply is exhausted, the submarine can still function as a conventional submarine with its diesel engines and batteries [5].

1.3 ACKNOWLEDGEMENTS

First of all I would like to thank Kockums AB for allowing me to take part of the development process of the new A26 submarine and for giving me the opportunity to conduct this thesis for them. A special thanks goes to Per Malmborg at Kockums Automation who was the one starting this project and giving me the opportunity to conduct it.

Secondly I would like to thank my supervisors, Magnus Fast at Kockums AB and Gunnar Lindstedt and Henriette Weibull, at the *Division of Industrial Electrical Engineering and Automation* at the Faculty of Engineering at Lund University, for their help, support and guidance.

Other persons at KAB that have really helped me with answering my questions and taken the time to give me the information I needed:

- Joakim Davidson
- Pekka Skogberg
- Johan Eriksson
- Jon Grekula

Without your help this work would never have been possible.

Finally I would like to send my appreciations and thanks to all the other personnel at Kockums AB that have shown interest in my work and helped and supported me and made me feel welcome at Kockums in Malmö.

2 PROBLEM FORMULATION

2.1 BACKGROUND

Traditionally the maintenance of different components and systems in submarines is conducted at given intervals and according to given instructions based on estimated or assumed lifetimes, in a preventive manner. This is however not always the most optimal solution from an availability and cost perspective since maintenance is performed independently of the item's current status.

As a way to increase the availability of submarines and reduce the maintenance costs Kockums wants to investigate the possibility of introducing a condition based maintenance (CBM) system in their submarines, something that in turn requires condition monitoring.

2.2 PROJECT DESCRIPTION

This project is a feasibility study that intends to examine the possibilities with condition based maintenance, if and how it can be implemented in the new A26 submarine, in what parts of the ship it is technically possible, what the gain of it would be etc. To increase the plausibility of a future implementation, it is primarily already existing sensors, data monitoring systems and data storage systems that should be utilized.

2.3 DELIMITATIONS

The following delimitations have been made:

- Primarily already existing sensors, data monitoring systems and data storage systems are investigated to increase the plausibility of a future implementation.
- A detailed system study of how CBM can be implemented on a particular system is made on the diesel engines only. Surrounding and connecting systems such as the generators are not considered.
- Which systems that should be part of a possible CBM system are not investigated in this project.
- How different particular errors develop in the diesel engines is not addressed.
- How different features of the diesel engines, e.g. vibrations, change due to different run modes and working environments is not investigated in this project.

2.4 OUTLINE OF THE THESIS

This thesis is divided in four major parts. First are descriptions and definitions of what is meant by maintenance and different kinds of maintenance strategies. The second part contains a detailed description of what condition based maintenance means and different ways of implementing it. The third part is a study of what a CBM system could look like on the A26 submarine, what the possibilities are and considerations that have to be made. The fourth part is a detailed case study of what a CBM program could look like in the diesel engines. The thesis finishes with a chapter addressing further research that should be made.

3 MAINTENANCE

This chapter aims to provide a brief overview of what maintenance is, with some definitions and a brief description of different maintenance strategies with advantages and drawbacks of each strategy. This chapter also includes a brief description of the four states of machine health and how different maintenance strategies handle them.

3.1 DEFINITIONS

In order to define maintenance, the term machine health needs to be defined and understood. SEMA-TEC, a company specialized in maintenance strategies, defines machine health as follows [6]:

> *“machine health is the state of a machine with respect to wear and damages as well as electrical, dynamical and geometrical properties that affect the machine’s availability, maintenance costs, functionality and ability to perform intended work with intended speed and quality”*

With this definition one can define maintenance as [6]:

> *“maintenance refers to all activities intending to uphold or restore units’ machine health to previous or defined levels”*

3.2 MAINTENANCE STRATEGIES

Maintenance strategies refer to the long time plan for how to uphold the machine health of a machine or system. Generally, maintenance can be divided into two different categories, Corrective Maintenance (CM) (to *“restore”* a unit’s machine health) and Preventive Maintenance (PM) (to *“uphold”* a unit’s machine health). These two categories can then further be divided into the four principal maintenance strategies; Immediate, Deferred, Scheduled, and Condition based, see Figure 3.1.

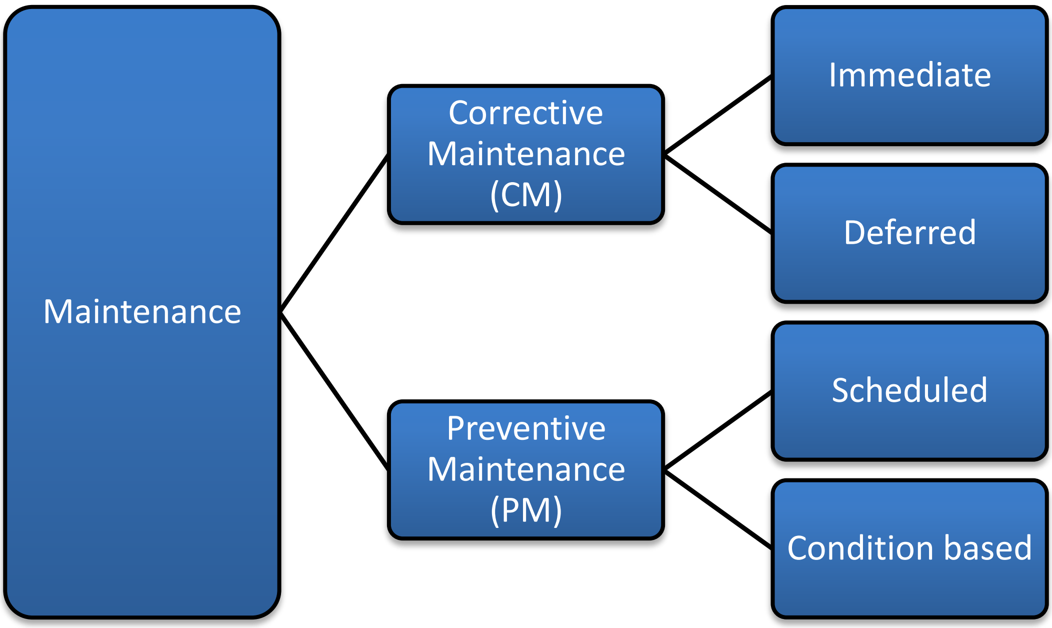

Figure 3.1 Principle maintenance strategies (source: [6]).

3.2.1 CM – CORRECTIVE MAINTENANCE

This strategy, sometimes called the 'run to failure' method, is simple and straight forward. It basically means that you run the machine until it breaks down. The breakdown may then lead to an immediate stop where the damaged component is repaired or replaced before the process is started up again (immediate maintenance). In case the damaged component is however not immediately critical to the continuation of the process the breakdown instead leads to a deferred reparation/replacement (deferred maintenance). CM can be compared to how a light bulb is usually maintained; nothing is done until it breaks, and when it does the power is switched off, the broken light bulb is replaced and then the power is switched back on again.

This strategy is appropriate for systems that are easy to maintain and where the components are cheap and can be replaced quickly with minimal cost and inconvenience. A requirement for this strategy is that an unplanned and unexpected failure will not have any critical effects on the overall process in which the system is involved.

There are however several drawbacks with CM. For instance, it is with this strategy impossible to make up a maintenance plan and unexpected critical machine failures may occur at any time. Also, if the system is not regularly inspected, small undiscovered component failures may evolve and lead to costly system breakdowns which in turn may be a safety risk to personnel in the vicinity of the machine.

In the following table some advantages and drawbacks of CM are summarized [6]:

Table 3.1 Advantages and drawbacks with CM (source: [6]).

Advantages	Drawbacks
Appropriate for systems that are easy to maintain or have a low replacement cost	Unexpected critical machine failures
Appropriate for systems where no costly side effects occur due to failures	Impossible to plan maintenance actions
No or limited need for investment in qualifications or technology	Minor damages are not discovered which may cause costly failures
	Risk of personnel injuries due to unexpected failures

3.2.2 PM – PREVENTIVE MAINTENANCE

PM is a maintenance plan which means that the system is supposed to be inspected, maintained and, if necessary, repaired or replaced in a preventive manner before there is a severe failure or breakdown. This can be done using either a scheduled maintenance (SM) strategy or a condition based maintenance (CBM) strategy.

3.2.2.1 SM – SCHEDULED MAINTENANCE

This strategy means that overhauls are made regularly at certain, statistically calculated, fixed intervals based on calendar time, run time of the system in question, number of repetitions etc.

The main advantage with this strategy is that there is a significantly reduced risk of encountering critical system failures compared to CM strategies. Also, it enables to plan for when maintenance will occur which means it is easier to prepare for. Basically all of the drawbacks with the CM strategies can be avoided, although there are other drawbacks with this strategy instead. For instance, this method will inevitably cause unnecessary overhauls of components, resulting in increased maintenance costs, components being replaced with many hours of useful life remaining, and reduced machine availability [7]. The correlation between a system's availability and downtime (due to for example maintenance) can be seen in Figure 3.2 and (1). Unnecessary overhauls could also lead to induced failures in the system that would not occur if the overhaul was never conducted, often referred to as maintenance induced failures.

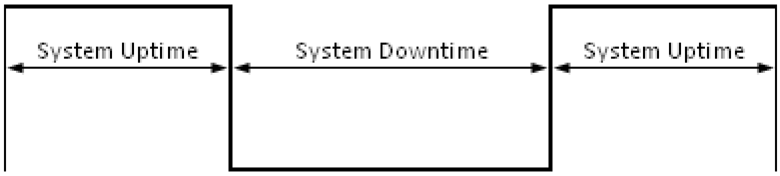

Figure 3.2 System uptime and downtime due to e.g. maintenance (source: [2]).

$$\text{Availability A} = \frac{\text{System Uptime}}{\text{Total time}} = \frac{\text{System Uptime}}{\text{System Uptime+System Downtime}} \tag{1}$$

In the following table some advantages and drawbacks of SM are summarized [6]:

Table 3.2 Advantages and drawbacks with SM (source: [6]).

Advantages	Drawbacks
Reduced risk of critical emergency failures compared to CM	Costs for unnecessary spare parts and working hours
Enables planning of the maintenance	Risk of machines being over-maintained
	Costs for unnecessary downtime

3.2.2.2 CBM – CONDITION BASED MAINTENANCE

CBM is the most advanced strategy of the four. By using different kinds of transducers and sensors, information about the state of the machine and the machine health is obtained. This information is then used to estimate and predict the optimal time for maintenance actions. The obtained data does not only give information about when an item is about to break down but also, for healthy items, gives a continuous "no fault"-indication that tells the operator that nothing is wrong and thus nothing has to be done. With this information one can avoid the unnecessary overhauls and other drawbacks that come with the SM strategy.

Some drawbacks with this strategy are that it could require a substantial investment and it may be a difficult approach to adopt since it requires qualified and cunning personnel.

A more detailed description of the CBM strategy with advantages, drawbacks, prerequisites etc. is presented in chapter 4.

In the following table some advantages and drawbacks of CBM are summarized [6]:

Table 3.3 Advantages and drawbacks with CBM (source: [6]).

Advantages	Drawbacks
Correct maintenance action at the right time	Substantial investment cost
Planned maintenance actions instead of emergency actions	Risk of machines being maintained too soon
Minor errors discovered in time before they develop and cause critical damage to the machine	Can be a difficult maintenance approach to establish
Critical failures due to wear can be reduced by almost 100%	
Continuous “no fault”-detection	

3.3 THE FOUR STATES OF MACHINE HEALTH

Machine health can be divided into four principal states; *Normal operation*, *Raised levels*, *Damaged machine* and *Critical failure* [6].

1. **Normal operation**
   The state in which the machine health is as good as it gets. The machine is able to perform its intended work with its intended speed and quality.
2. **Raised levels**
   The machine is experiencing raised levels in machine health related fields such as vibrations, temperatures, pressures etc. which can be discovered with CBM. The machine is on the way to being damaged and it might not be able to perform its intended work with its intended speed and/or quality.
3. **Damaged machine**
   The machine is slightly damaged but still able to operate, although it is not able to perform its intended work with its intended speed and/or quality.
4. **Critical failure**
   The machine has experienced a complete break down and is in need of immediate reparation.

The four states of machine health and how the different maintenance strategies handle them are shown in Figure 3.3 [6]:

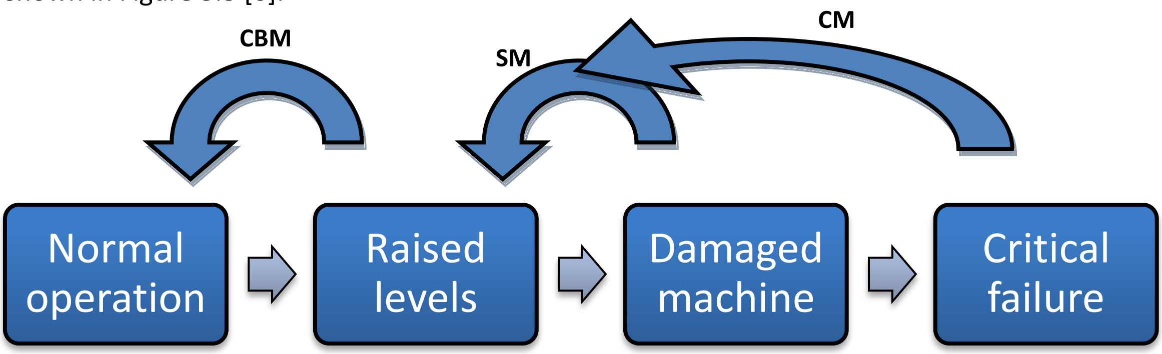

Figure 3.3 The four states of machine health (source [6]).

CBM can detect errors already in the second state, *Raised levels*. With that information a maintenance action can be planned before the machine/system gets damaged which means the third and fourth state, *Damaged machine* and *Critical failure*, never have to be reached.

SM might not detect and correct raised levels which means the machine/system could reach the third state, *Damaged machine*. When the maintenance action is then performed the damage might get fixed but the underlying, sometimes hidden, problem which causes raised levels might not, which means the machine will only go back to the second state, *Raised levels*.

With a CM strategy the machine will always run until it reaches the fourth state, *Critical failure*. That is the definition of CM. For the same reasons as with SM, the underlying problem which causes the break down might not get fixed during the maintenance which means the machine will only go back to the second state, *Raised levels*, after maintenance.

4 CONDITION BASED MAINTENANCE

This chapter aims to give a detailed description of CBM, how it works, what is required for it to work properly, how an effective CBM system should function and different ways of implementing it. The chapter also includes a section with different measurement techniques for condition monitoring.

4.1 BASICS

As mentioned earlier CBM requires condition monitoring which is a methodology for obtaining information regarding the state of health of specific machines and identifying the correct maintenance action at the optimal time [6], or more formally [8]:

> *"The continuous or periodic measurement and interpretation of data to indicate the condition of an item to determine the need for maintenance"*

CBM thereby requires means for obtaining such machine health related information. Generally it means different types of measurements, e.g. vibration measurements, thermography, ultrasonic measurements or oil analysis, for more information on different types of measurement techniques see section 4.6.

4.2 THE CBM PROCESS

The maintenance process of CBM consists of five sequential steps as shown in Figure 4.1.

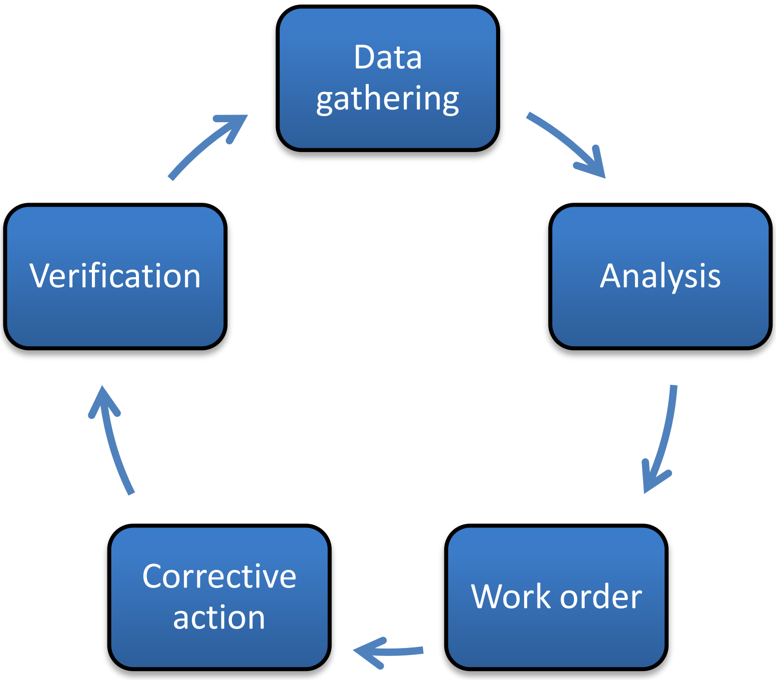

Figure 4.1 The maintenance process of CBM (source: [6]).

1. **Data gathering**
   The first step in the CBM process is to gather data regarding the machine health e.g. vibrations, pressures, temperatures etc. This is performed while the item is in its operating state to increase the reliability of the measurements [9]. It can be done either continuously with transducers and/or sensors with a permanently installed system (PIS) or scheduled or on request with a round based system [9], as described in section 4.5. The gathered data is usually stored in a database.

2. **Analysis**
   The gathered data is then analyzed to see if there are any deviations compared to the normal operating values and if there is anything wrong with the machine, and in that case; what is wrong and what can be done to fix the problem. This analysis can be done either automatically by an analysis software program or manually by a maintenance technician [6],[9]. An automatic analysis can be either specific, i.e. the program analyzes the data and establishes exactly what is wrong with the machine, or general, i.e. the program can say that there is something wrong with the machine but cannot say exactly what or where.
   In a lot of cases the two approaches (automatic and manual) are combined – an automated program analyzes the data and indicates that there is something wrong and then a technician analyzes it further to establish what and where the problem is.
3. **Work order**
   If the analysis shows that there is something wrong with the machine a work order is placed to fix the problem.
4. **Corrective action**
   The machine is maintained/repaired to restore the machine health to normal operation levels (Figure 3.3).
5. **Verification**
   After the corrective action is performed, data is gathered and analyzed again to verify that the problem is fixed and that the machine health is restored to normal operation levels again.

4.3 PREREQUISITES

The most fundamental prerequisite for CBM is that the monitored system/component has an error development time, i.e. the time from when an error or abnormality first occur in the machine (Raised levels) until the machine completely breaks down (Critical failure). Most machines develop small abnormalities prior to complete breakdown, however, for some machines, failure may occur instantaneously with no development time at all [7]. The whole point of CBM is that one can detect abnormalities in the system before it breaks down and use that information to predict when the system will fail and plan a maintenance action according to that. If the system does not have an (or have a very short) error development time, one cannot predict when to maintain the machine and the system might break down without notice. In those cases an SM strategy is preferable. The different error development time situations are illustrated in Figure 4.2 and Figure 4.3. Figure 4.2 illustrates the case with a considerable error development time when deviations from the normal operation levels can be detected some time before the system breaks down and a maintenance action can be planned. Figure 4.3 illustrates the case with no, or a very short, error development time which means there is no possible way to beforehand predict a system breakdown.

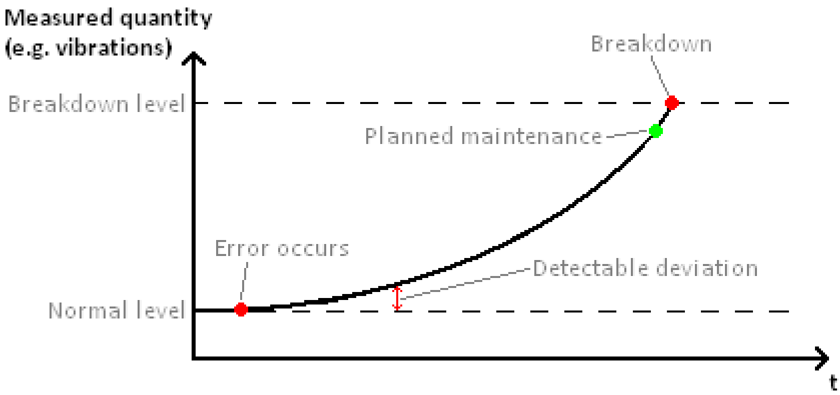

Figure 4.2 Considerable error development time. Normal level and breakdown level equivalent to normal operation and critical failure respectively in Figure 3.3.

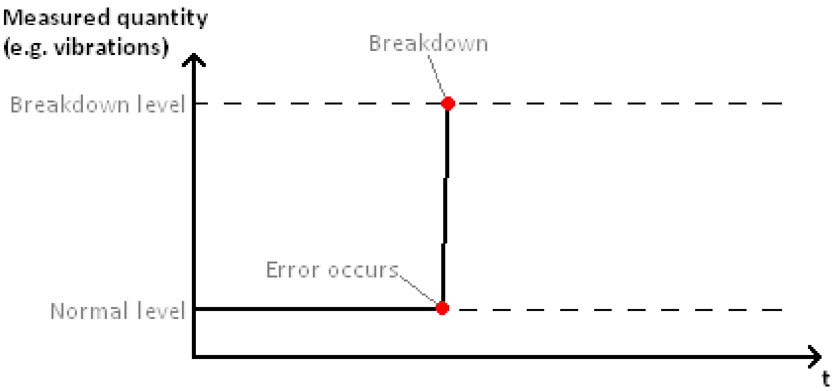

Figure 4.3 Short error development time. Normal level and breakdown level equivalent to normal operation and critical failure respectively in Figure 3.3.

Another important prerequisite is that one has to know what the normal operation levels are for the monitored quantity (e.g. vibrations). If those levels are not known one might believe that a machine is perfectly healthy when in fact the vibrations might be much higher than what is good for the machine and the machine might break down sooner than predicted (missed alarms [7]). On the other hand one might believe that a machine is closer to a critical failure than it actually is which results in unnecessary maintenance actions (false alarms [7]).

To be able to predict when the system might break down and to plan the maintenance one also needs to know how the machine works and reacts to different working environments and run modes as well as how different errors develop. If one does not know that, it is impossible to interpret and make an accurate analysis of the gathered monitored data. For example if an increase of vibrations in one part of the machine is detected one have to know what causes those kinds of vibrations to be able to make an accurate “diagnosis” of the problem. The increase in vibrations might be caused by faults in the machine, changes in the run mode or changes in the working environment such as temperature changes, pressure changes, humidity changes etc. Therefore, run mode and environment properties have to be accounted for when establishing the normal operation levels and breakdown levels to be able to determine when changes in the measured property is due to faults in the machine and nothing else. How this can be done is further described in section 4.4. If an incorrect diagnosis is made, the wrong maintenance action might be performed and the wrong component might get replaced, which means unnecessary costs and downtime and maybe even a critical failure of the machine later on if there is a problem that does not get fixed at all due to the faulty maintenance action.

4.4 THE SMART CBM SYSTEM

As mentioned earlier it is important to know how the monitored machine/system reacts to external properties such as the working environment and run mode. A change of run mode might cause a change in the monitored properties and one does not want that to lead to an unnecessary maintenance action.

An efficient CBM system does not have specific set cut-off levels and a machine/system that shuts down and is scheduled for maintenance as soon as the monitored values get less or greater than the set cut-off levels. An efficient CBM system takes into account the current run mode of the system as well as the working environment to establish what levels should be expected for a healthy system. The actual measured levels are then compared to the expected levels and analyzed to see if there is something wrong with the machine or not. If there is a difference between the measured levels and the expected levels the CBM system again takes into account the current run mode, environment and how the values differ, to make a prediction of when the machine will fail so that a maintenance action can be planned before there is a critical breakdown.

A big part of CBM is thus not just condition monitoring but also to establish the expected levels for a healthy system. This can be done in various ways. One way is to make measurements of a healthy system over time and build up a database with levels for all kinds of different run modes and environments. This however requires that one has both time and an available machine to make all those measurements. Another drawback with this method is that every machine individual is slightly different from another and if measurements are made on one machine those results might not be completely accurate for another machine individual of the same type. There is also the problem that one can never be sure that the machine used for establishing the healthy levels actually is healthy.

Another way to obtain the healthy levels is to make a computer model of the machine, which uses the run mode and different environment parameters as inputs to calculate the healthy levels. This can be done either by using physical laws and machine parameters or by using for example artificial neural networks (ANN) that can learn from a machine how the expected values should be calculated. The problem with using physical laws and machine parameters to construct a computer model is that all the machine parameters can be difficult to obtain if the machine is manufactured by another company that does not want to reveal specific machine data. In that sense artificial neural networks are better since one does not need any of the machine parameters to generate the model, although one need machine measurement data that the ANN can learn from and with that comes some of the same drawbacks described earlier with making measurements of an existing machine. For more information about ANN and how it can be used for monitoring gas turbines, *Artificial Neural Networks for Gas Turbine Monitoring* [10] is recommended.

4.5 PERMANENT OR ROUND BASED

CBM can be based on either a permanently installed system (PIS), a round based system or a combination of both.

A PIS is based on sensors and transducers that are permanently installed on all relevant places in the monitored machine/system. Monitored data are automatically continuously gathered, stored and analyzed as described in section 4.2. This method is preferable due to the fact that it can perform measurements with very short intervals, basically in real time. This is desirable because it gives the opportunity to detect errors at a very early stage and thereby makes it possible to plan maintenance actions in greater advance as well as being able to use CBM on components with shorter error development times. The drawback with the PIS though is that the initial cost might be relatively high due to the amount of data acquisition electronics and sensors that has to be purchased and installed. However, in the long run it is usually the most economic solution since this method does not acquire much, or any, manual monitoring.

A round based system is based on portable sensors and data acquisition devices, thus all measurements have to be made manually by a technician. For example vibrations can be measured by a portable sensor that is placed on the monitored component with a magnet [6]. The technician can then store vibration data on a portable device, remove the sensor when all necessary data is acquired, and move along to make measurements on another component. These rounds of measurements are made periodically as often as necessary, however, measurements can never be done with as short intervals as with the PIS. This approach has a lower initial cost compared to the PIS since not as many sensors and as much data acquisition electronics have to be purchased and installed. However there are some drawbacks, for example, if the sensor is not placed at the exact same place every time measurements are made, the result might vary which can lead to a misinterpretation of the machine health. Also a lot of machines and components can be geographically difficult or unsafe for humans to access. In those cases monitoring with this method is not possible. Another drawback is that there is always a risk that the technician makes mistakes, such as measuring vibrations on one component but storing them as vibrations for another component, which can easily lead to erroneous analyzes of components which in turn lead to erroneous maintenance actions. Such errors can however be somewhat prevented with scanning systems, which means that the technician have to scan a tag on the component before storing the measured data so that the data gets automatically stored as vibrations for the right component.

A usual approach is to use a combination of the two methods. On the inaccessible machines or components it is suitable to use a PIS and on the more accessible and less safety critical components the round based system can be used. Machines suffering from errors with short development times should also be monitored with a PIS instead of a round based system. For example if an error has an error development time of five hours from raised levels to critical failure, see Figure 3.3, and the measurement rounds are only made once every day, the raised levels might not get detected before the machine has a critical failure. If the machine however was monitored in more or less real time with a PIS the raised levels could be detected after only a few seconds and something could be done to prevent a critical failure or breakdown.

4.6 MEASUREMENT TECHNIQUES

There are several kinds of measurements that can be made to be able to determine a machine’s state of health in condition monitoring. What kind of measurement technique that should be used depends on what kind of machine it is, what kind of machine health related information one want to obtain, how much the monitoring can cost, etc. Here is a brief overview of the most commonly used techniques.

4.6.1 VIBRATIONS

Vibration measurements is the most commonly used technique of all and it is well established in the paper- and process industry since the 1960’s and 1970’s. In some industries CBM is basically equivalent with vibration measurements and there are good reasons [6]:

- Works on basically all kinds of machines.
- Can detect a majority of the known failures for most kinds of machines.
- Can detect non predicted kinds of failures.
- Works with both PIS and round based systems.
- Can usually be used without interfering with the production.
- Gives information about deviations at an early stage of the error development time.

Some machine errors that can be detected with vibration measurements are [6]:

- Imbalance in rotors.
- Misalignment between bearings.
- Misalignment between axles.
- Bent axle.
- Mechanical gap, e.g. some part has come loose.
- Mechanical impact, e.g. rotor touching the stator.
- All kinds of bearing damages.
- Bearing wears.
- Eccentric rotor.
- Resonance, i.e. critical RPM.

Vibration measurements are usually a good starting point for a CBM system since it can detect a lot of the most common kinds of errors. After establishing vibration measurements one can gradually complement the system with other kinds of measurement techniques that can detect errors that the vibration monitoring cannot.

4.6.2 PRESSURE AND FORCE

Dynamic pressure and force measurements are often used as a complement to vibration measurements, especially in pumps, hydraulic systems etc. For example; pressure measurements in addition to vibration measurements on a pump can determine which vibrations are due to mechanical problems and which are due to hydraulic effects.

Pressure measurements can also be used to detect frictions or to measure cutting forces in a processing machine or press forces in a press [6].

4.6.3 STRAIN

Strain measurements can be used to monitor a structure's structural integrity and shape, e.g. tanks, foundations, or pipes.

Strain can also be used as a way to measure force where force transducers are difficult to apply. It is a good way to measure frictions as well, for example if the friction in a valve increases the force required to open and close it increases as well and the signal from the strain gage will change accordingly. Strain gages are usually cheaper and easier to apply compared to force transducers [6].

4.6.4 ULTRASONIC

Ultrasonic measurements are used to detect sounds with frequencies higher than those audible to humans. Machine errors that may cause such sounds could be compressed air leakages or bad electrical contacts in relays. Ultrasonic measurements could also be used to examine material thickness and weld joints [6].

4.6.5 THERMOGRAPHY

Thermography, or heat photography, means that an object's IR (infrared) signature is photographed. This kind of monitoring has many advantages compared to conventional temperature measurements. First of all it is a non-contact measurement technique, which means electrical and rotating parts of a machine can be monitored without endangering the user. Also the photography does not affect the monitored object since the camera only detects the radiated heat. The second main advantage is that the camera can measure the temperature of the whole monitored object at once, while conventional temperature measurements can only measure the temperature in one point at a time. This means that with thermography one can easily compare temperatures in different parts of the component [6].

In CBM, thermography is mainly used for [6]:

- Maintenance and monitoring of electrical systems
- Monitoring of buildings
- Maintenance and monitoring of furnaces and boilers
- Mechanical monitoring, friction and wear
- Monitoring of flow and leakage
- Monitoring of levels in tanks and containers
- Energy optimization

4.6.6 ELECTRICAL CURRENT AND VOLTAGE

Dynamic measurements of electrical current and voltage can be used for monitoring a machine's state of health on all kinds of machines that produce or consume electrical energy. Almost all kinds of electrical errors can be detected by measuring currents and voltages. Even some mechanical errors can be detected, for example if there is a bearing failure or friction is induced between two parts in a servomotor the electrical signature from the motor will change, which can easily be detected [6].

4.6.7 SOUND

Sound measurements have traditionally been used mainly in the same way and for the same purposes as vibration measurements, i.e. to detect bearing damages or imbalances etc. However, sound measurements are more difficult to analyze and the results are more uncertain compared to vibration measurements. Today, sound measurements are mainly used on objects that are too hot for vibration transducers to attach to [6].

4.6.8 OIL ANALYSIS

The term machine health, see section 3.1, also includes oil quality. For one who wishes to avoid unnecessary oil changes, oil measurements are a good idea. Traditionally, oil analyzes are made by taking a sample of the oil and analyzing it in a laboratory. However, new types of sensors for PIS's have been developed lately that can measure basic properties of the oil, such as viscosity, density, temperature and dielectric constant [6].

4.7 SENSOR VALIDATION

Since maintenance decisions are always made based on sensor measurements in a CBM system, the sensors used to make the measurements need to be validated. If not, there might be something wrong with the sensor and the interpretation of the machine health will be incorrect. For example, if a sensor is measuring the temperature in some part of a machine and the temperature is 150 degrees, but the sensor is failing and shows 180 degrees, that would probably be interpreted as a machine failure and lead to a faulty maintenance action. Thus, validating the sensors and the measured values is of great importance in order to avoid faulty maintenance actions based on faulty information.

There are different ways to do this. One way is to compare the measured values to a physical equation, e.g. the energy equation, and see if it adds up. If not, one can conclude that a sensor might be failing. Another way is to use an ANN where the network is trained to estimate the corresponding input values from the outputs, the input values in this case being the sensor values. By comparing the estimated inputs to the actual measured inputs one can determine if a sensor is failing. For more information about these two methods, *Artificial Neural Networks for Gas Turbine Monitoring* [10] is recommended.

5 CBM ON A26

This chapter aims to describe and discuss the possibilities and the possible effects of introducing CBM on the A26 submarine. As mentioned in the project description, section 2.2, it is primarily already existing sensors, data monitoring systems and data storage systems that should be utilized. First is a short description of things that have to be considered when introducing CBM on a submarine, followed by a description of the existing control and monitoring system, which will be a central part of introducing condition monitoring. Following, the possibilities concerning data acquisition and data storage are addressed, followed by what is needed, but still does not exist on the submarine today, to have an effective CBM system. Lastly is a discussion of what effects CBM may have on the maintenance plan of the ship as well as on KAB's relation to its costumers regarding through life support (TLS).

5.1 CONSIDERATIONS

Introducing CBM on a submarine is not like introducing it in any other land based machinery. A submarine has a few properties that have to be considered, for example [6]:

- A submarine is compact with all machines in a small area.
- A submarine has a lot of different machine types but usually just a few units of each type.
- There are few submarines of the same type and thus limited possibilities to build up statistical data.
- Maintenance has far reaching implications for:
  - Operational availability.
  - Personnel and crew safety.
  - LCC – Life Cycle Cost.
  - The submarine's signature.
  - The submarine's ability to listen.

The compact arrangement on submarines with all machines in a small area affects the choice of CBM system. Generally, compact facilities are cheaper monitored with a PIS than with a round based system. However, the compact arrangement might make it difficult to make room for additional sensors and cables that might be needed for condition monitoring with a PIS.

The large number of different machines but the few numbers of units of each type also affects the choice of monitoring technique. With few machine individuals of each type on each submarine, and the few amount of submarines of each class, the statistical reference data gets limited. Thus the importance of high quality measurements with short intervals increases, which also suggests a PIS.

An important part of a submarines signature is sound or noise from machines on board, usually originating from vibrations. Since vibration monitoring is one of the most commonly used measuring techniques in a CBM system (see section 4.6.1) there is a strong connection between CBM and signature control on submarines. By monitoring the vibrations from the machines the noise generation can be reduced and in most cases the vibration monitoring can detect a potential noise problem well before the noise becomes an incriminating factor.

Vibration monitoring can also help improving a submarine's listening capabilities. Vibrations caused by the machines on board the submarine might cause noises in the exact same frequency ranges as used when listening for alien ships. If one's own vibrations are monitored, internal machine health problems, and the noises originating from those, can be accounted for when analyzing what the sonar is registering.

If CBM is to be utilized or not depends on the investigated system. To determine which systems should be a part of a potential CBM program or not, one have to look into each system individually in detail. One has to keep in mind that some components/machines actually may benefit financially from a CM system or a SM system. However, systems that are capital intense, safety critical, difficult or costly to replace etc. would most likely benefit from a CBM system [9].

Another thing that has to be considered when deciding if and/or what kind of CBM system that should be implemented is that not all maintenance actions will be affected no matter how advanced the CBM system is. There are parts of the ship that cannot possibly be monitored by any sensors and there are maintenance tasks that will always have to be conducted no matter if the submarine is being monitored or not. The cleaning and repainting of the hull for example cannot be monitored by sensors and sludge suction and cleaning of the inside of the submarine will always have to be done during the annual overhauls. When estimating how the total maintenance plan will be affected by a proposed CBM system one has to consider which maintenance tasks can, and which cannot, be affected by the system. How will the maintenance plan be affected and how many percent of the total maintenance can be affected by a CBM system and how much is it allowed to cost?

One also has to consider what the recommendations from the external suppliers are regarding maintenance for the machine. Changes in the recommended maintenance plan for a machine might mean that the warranty does not apply anymore, which could be very costly in case anything should go wrong. If the CBM system is properly implemented and functioning nothing should go wrong but there is always a risk that something completely unexpected occurs, especially if there is an error occurring with no, or very short, development time, see section 4.3.

5.2 SCMS – SHIP CONTROL AND MONITORING SYSTEM

On board the A26 there is a Ship Control and Monitoring System (SCMS), which is a system for controlling and monitoring the entire submarine. It can be operated from a primary operator console in the control room as well as from a secondary operator console in the aft with the same functionality as the primary. This means that the entire submarine can be controlled both from the control room and from the aft if needed. All information, signals and commands on the ship are integrated with SCMS, see Figure 5.1.

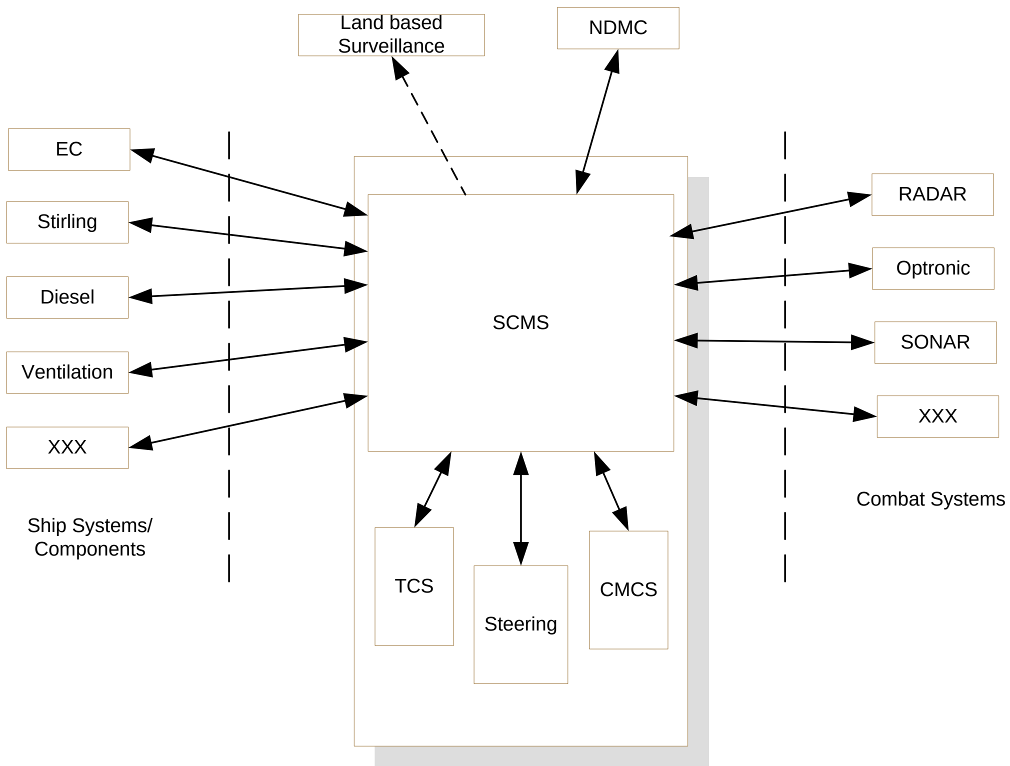

Figure 5.1 Systems and components communicating with the SCMS (source: [11]).

From a CBM point of view, the connection between the SCMS and the ship systems/components is of great interest. Below is an excerpt of systems/components that are monitored and/or controlled by the SCMS [2]:

- Masts
- Diesel engines
- Diesel engine generators
- Air intake, snort and exhaust system
- Diesel engine cooling system
- Stirling engines
- Main battery monitoring system
- DC network, battery voltage
- Shore connection
- Heating system
- Ventilation system
- Air condition system
- Sea water cooling system
- Bilge and drainage system
- Daily bilge system
- Weight compensating system
- Trim system
- Diving and ballast system
- Hot water system
- Compressed air system
- Weapon tubes
- Countermeasure launch system
- Degaussing system
- …

It is obvious that basically everything on board the ship is monitored and integrated with the SCMS which means it is ideal for a CBM system.

The SCMS is built up in four layers, the User Interface layer, the Gateway layer, the Process layer, and the Ship System Interface layer, see Figure 5.2.

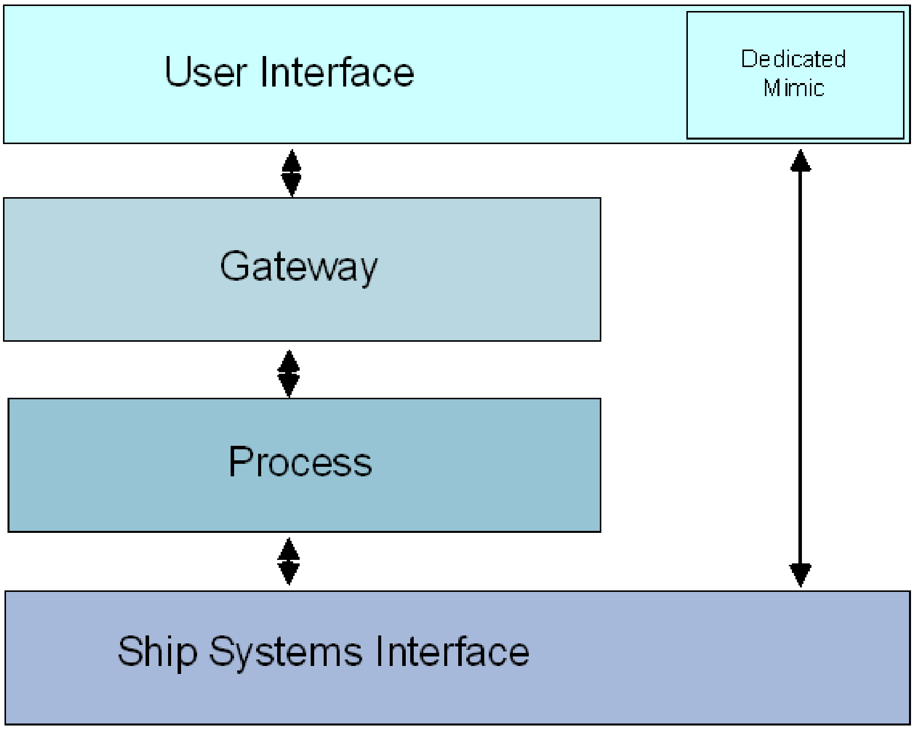

Figure 5.2 The four layers of the SCMS (source: [11]).

1. **User Interface layer**
   This layer represents the interface between the operator and the control logic. Its main functions are to present information to the operator and send control commands to the gateway layer. It consists of displays, computers, software and interaction devices such as touch screens etc [11].
2. **Gateway layer**
   This layer contains software and hardware necessary to transfer signals and information between the user interface layer and the process [11].
3. **Process layer**
   This layer coordinates all activities within the system, processes commands, make the logical decisions and evaluations, as well as performing calculations, i.e. the core of the control system [11].
4. **Ship System Interface layer**
   This layer represents the interface between the control logic and the real world objects, i.e. transmitters, valves, pushbuttons, indicators, sensors etc. The layer consists of I/O-nodes distributed throughout the ship [11].

The SCMS is based on a redundant PLC system, built up with two identical PLCs, Master and Slave, synchronized by a fiber optic connection. The slave is continuously updated and ready to take over control should the Master fail. In case one of them fails it is easy to replace and the new one is automatically updated from the other and ready to operate within a few minutes [12].

The I/O-nodes in the Ship System Interface layer are module built with different types of both digital and analog input and output modules. Several communication protocols are used for the communication between sensors and systems and the SCMS supports all of the following [11]:

- Ethernet Powerlink
- Profibus DP
- Ethernet with TCP/IP or UDP/IP
- Ethernet IP
- ProfiNet
- Point-to-Point (RS232/422/485)
- CAN Open / CAN-bus
- Modbus RTU (RS422/485)

These features makes introduction of new kinds of sensors and systems relatively easy, which makes it very suitable for introducing a condition monitoring system.

The structure of the SCMS is shown in Figure 5.3 and the locations of the operator consoles, the data servers and the I/O nodes in the submarine are shown in Figure 5.4.

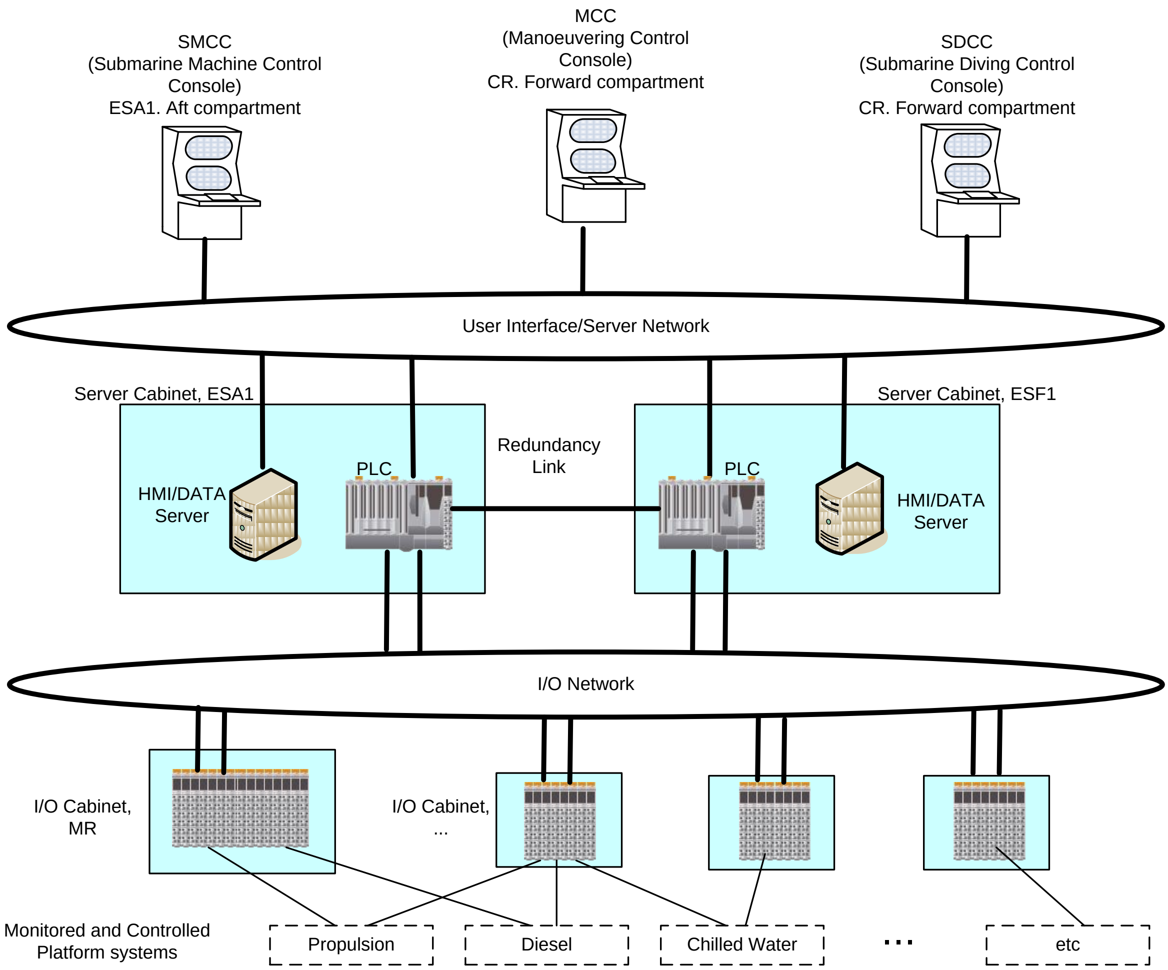

Figure 5.3 The SCMS structure (source: [11]).

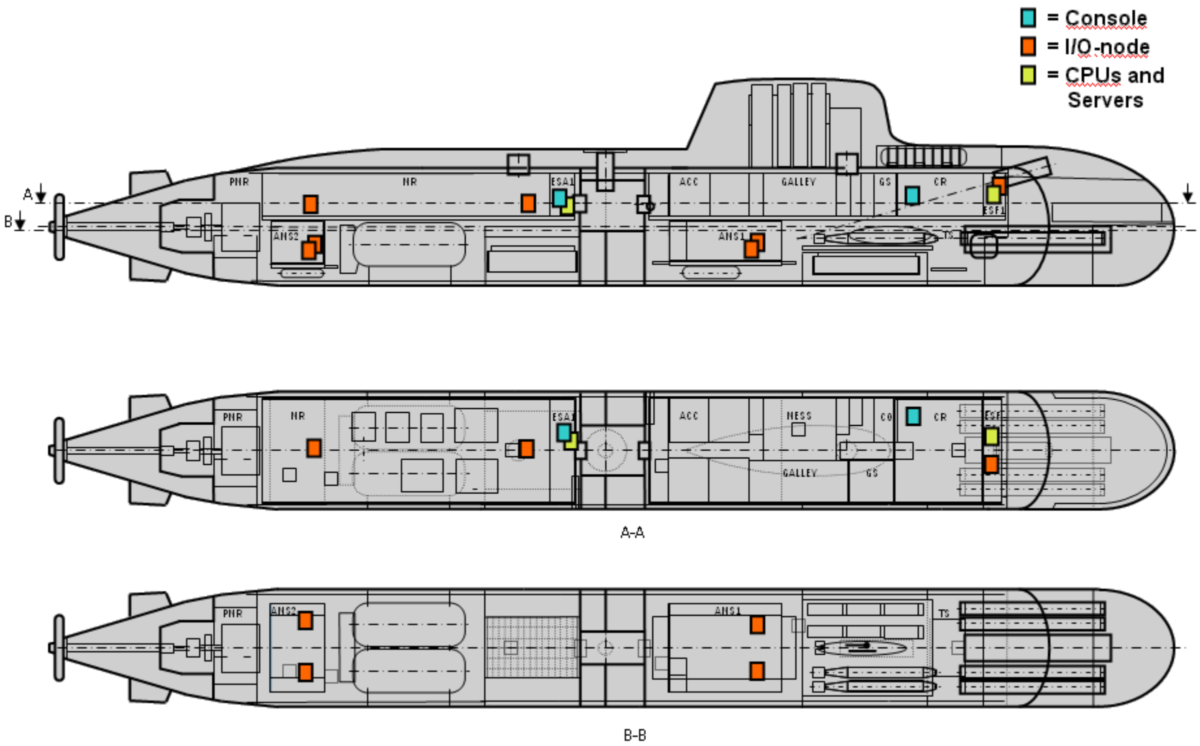

Figure 5.4 The locations of the operator consoles, data servers, and I/O-nodes of the SCMS (source: [11]).

5.3 POSSIBILITIES

5.3.1 DATA ACQUISITION

To acquire data, one must have sensors to make measurements. There already exist a lot of various sensors in each system on the submarine to monitor what is going on everywhere. However, the question is; is it enough and do they measure the right thing from a CBM point of view? To answer that question one need to evaluate and look into each subsystem individually in greater detail. For example, for the diesel engines one has to investigate and determine what kind of measurements are required to be able to make an accurate diagnosis of its machine health and then see if there are any existing sensors available to make those measurements. If not, one has to consider if it is possible to buy and install new sensors to make the required measurements. With all the I/O-node modules spread out throughout the ship, a PIS is very appealing, since it should not be any problem to add new sensors to the already existing SCMS, especially not since the SCMS should be *"prepared for integrating online monitoring of parameters essential for condition based maintenance such as vibration, temperature and pressure"* [11]. However, sensors are not exactly "plug-and-play". New signals from a newly installed sensor first have to be added in the system and then it has to be calibrated and scaled to correspond to the right quantity. This is however fairly easy to do in the SCMS, the biggest problem with new sensors is not to add them to the SCMS but rather to make physical room for them and new cables and place them in the system/machine somehow [12].

5.3.2 DATA STORAGE

Since the SCMS already exists for the A26 submarine it is appropriate to make as much use of it as possible. It has a data logging feature and it is already logging data from installed systems, e.g. RPM and temperatures in the diesel engines. All analog signals are logged with a frequency of 1 Hz, or higher if desirable, and stored in a database on board the ship for an entire mission [12]. This makes a PIS very suitable. The User Interface layer of the SCMS then has the possibility to show history and trend curves of all stored data in the operator console, and trend curves for newly added signals can easily be added.

The SCMS also logs data that are not actually measured by sensors, but rather observed by the SCMS itself, e.g. number of start attempts, number of starts, or total running time for a motor. This can be done with simple logic counters in the software and can be valuable information for CBM purposes since such things might affect for example the vibrations in the motor and thus the expected values for the vibrations should change accordingly, see section 4.4.

How much data that can be stored in the database on board the ship is only limited by the hard drive capacity, which really is not a problem. The stored data does not take up much disk space on the hard drive and even if the stored data should be too much, the disk space could easily be expanded by adding another memory card.

5.3.3 ANALYSIS SOFTWARE

To be able to have an effective and well functioning CBM system one need to have software programs for analyzing the logged data. As for now, no such programs exist on the submarines. The SCMS however does have the capability to run the needed programs, either developed directly by KAB or bought from external suppliers and installed on the SCMS. This is further discussed in section 5.4.2.

Since all data could be stored in the same way on the same database, i.e. the SCMS, only one analysis software is needed for all the monitored systems. This is preferable since the implementation costs and/or development costs could be greatly reduced if only one program is needed and the crew and the maintenance personnel only have to be educated in one software instead of different programs for each machine.

5.4 NEEDS

5.4.1 DATA ACQUISITION AND DATA STORAGE

If new sensors are needed or not depends on which subsystem is investigated. As mentioned earlier one need to look into each subsystem individually in greater detail to determine if new sensors are needed or not.

Since the submarines of the new A26 class already have an SCMS, the problem with acquisition and storage of data is already solved if a PIS is chosen. This will greatly reduce the total investment costs of CBM (which can be relatively high for a PIS) since the data acquisition electronics does not have to be bought.

In case a round based system is chosen, portable data acquisition devices and sensors will have to be bought.

5.4.2 ANALYSIS SOFTWARE

As mentioned in section 5.3.3, analysis software programs are needed to have an effective and well functioning CBM system, and such programs does not exist on the submarines today. First of all, a program for calculating and estimating the expected values for each machine is needed. This can be done in different ways, explained in section 4.4. When that is established one need a program that compares the logged values to the estimated expected values to see if there are any deviations. If there are, the program either needs to alert the operator that something is wrong so that he/she can analyze it, or be able to analyze the deviations automatically to establish what is wrong with the machine. When that is done the program should predict when the machine will fail so that the correct maintenance action can be planned to be performed at the right time, see section 4.2.

The question is; should KAB develop such software systems themselves or should they buy existing products from external suppliers? If KAB decides to develop their own analysis software a substantial investment cost can be avoided, however the development costs might exceed the investment costs which would make it unjustified. Another thing that has the be considered is if KAB has the right knowledge and competence to develop such programs. If KAB decides to buy existing programs from external suppliers, installing them on the SCMS is not a problem. This makes buying existing programs appealing since the programs would then be developed by experts in the field and therefore one could be confident it will work desirably, and the risk of rapidly increasing development costs can be avoided.

5.4.3 OPERATING DATA OR MACHINE PARAMETERS

To be able to establish the expected values of a measured quantity one need to have either operating data of different run modes of the system/machine in question or detailed information about the machine parameters, see section 4.4. Since all the stored data after each mission is stored by the Swedish Armed Forces and not available to KAB, operating data is today difficult to use and machine parameters or detailed computer models of the machine are usually hard to get from external suppliers. This is a problem since establishing the expected values is critical to an efficient and well functioning CBM system. Although, some expected values for different run modes for some systems/machines might be able to get from the suppliers.

The Stirling system however is developed by KAB which should make it possible to easily acquire all the necessary data and measurements in the laboratory that are needed to introduce CBM.

5.5 EFFECTS

5.5.1 SUBMARINE MAINTENANCE PLAN TODAY

The maintenance plan for the A26 submarine is today not yet completed, however it looks today like it will probably look a lot like the maintenance plan for the Gotland class submarines. The maintenance of the Gotland class submarines, which are the newest and most modern submarines in the Royal Swedish Navy today (see section 1.2.3), is divided in two levels; A and B.

1. **Level A**
   Level A maintenance is conducted by the crew on board the ship at sea and includes round based overhauls and maintenance actions. Depending on the item and its criticality it is performed every day, week, month, three months, six months, or year. Some items are also maintained based on hours of operation, e.g. 500 hours or 1000 hours [13].

2. **Level B**
   Level B maintenance is more extensive than level A maintenance and is conducted annually in drydock by specialized maintenance personnel or external specialists depending on the item. This annual maintenance is basically an overhaul of the majority of the submarine and is done once a year for the Gotland class submarines, with no exceptions. For the A26 submarine it is planned that this overhaul is only conducted once every second year [14]. This annual overhaul can take roughly two months to perform and by effecting the maintenance and reducing this downtime the availability of the submarine can be greatly increased.

5.5.2 POSSIBLE MAINTENANCE PLAN WITH A CBM SYSTEM

With a PIS on the submarine the level A maintenance and the workload on the crew could be significantly reduced since the system would monitor the items on board instead of letting the crew conduct round based overhauls. For example, there are today 88 different maintenance tasks on the Gotland class submarines that are supposed to be performed every day by the submarine crew, mainly simple overhauls and different functionality verifications [13]. If some of those could be monitored by a CBM system instead it would save the crew a lot of time. Also, instead of having a maintenance plan with maintenance actions planned with fixed intervals on board every day, week, month, three months, six months, or year, a smart CBM system could have a feature that every day tells the operator what maintenance actions should be performed for example today, this week, or next month. That way the crew does not have to follow a strict maintenance plan, just do what the analysis program tells them to do.

With a CBM, and the continuous "no fault"-indication that comes with it if there is nothing wrong with the monitored item, one may also be able to reduce the level B maintenance. For example if all sensors indicate that an item is healthy, maintenance on that particular item can be avoided the next annual overhaul. If this can be done for a number of items the downtime during the annual overhaul can easily be reduced by avoiding unnecessary maintenance actions.

5.5.3 TLS – THROUGH LIFE SUPPORT

Through life support (TLS) is a service currently under development at KAB. The idea is that instead of just developing, building and delivering submarines (and other ships as well), KAB will also take full responsibility for the maintenance of the ships. KAB wants to offer the customer a service where KAB takes full care of the maintenance (both planning and conducting), maximizes the availability of the ship, and ensures that the ship is operational when it needs to be [15].

Today the maintenance of the Swedish submarines is planned by the Swedish Royal Navy according to the maintenance manual given to them by KAB at the time the ships were delivered [15], e.g. in 1997-98 for the Gotland class submarines. Since the navy plans the maintenance, and KAB conducts it, there is no actual feedback and update of the maintenance plan, which means it may be obsolete and very far from optimal according to an availability- and cost point-of-view. If KAB has the responsibility to both plan and conduct the maintenance there can be a constant development, renewal and improvement of the maintenance plan.

By taking over the planning and the management of the maintenance, KAB will be able to charge the customer for that service through the whole life time of the ship, which is approximately 30 years for a submarine, and thereby generate a higher income. Another gain from selling this kind of TLS service would be that the customer would eventually be dependent on KAB for their continuing use of their submarines, which could in the long run be very beneficial to KAB. The selling argument for this service is that the customer will have a ship with a much greater availability, and thus it will be a win-win-situation.

With a CBM system implemented on the A26 submarine the maintenance can more easily be optimized and thus help KAB reach the goal to maximize the availability of the submarine. A CBM system alone might not contribute to all of the availability increase but it can help with a part of it and together with other changes and developments of the maintenance the desired availability increase can probably be accomplished. One have to keep in mind that TLS is not a service exclusively for the A26 submarines and there is a lot of other work behind the TLS service besides the maintenance part.

5.6 ADDITIONS

5.6.1 SELF MONITORING TRANSMITTERS

An important issue with CBM is sensor reliability and sensor validation. One thing that could be done to circumvent the problems described in section 4.7 is to use self monitoring transmitters. A self monitoring transmitter is a module with two sensor elements, measuring the same thing, i.e. a redundant transmitter. This solution makes it possible to detect sensor drift by monitoring the difference between the two sensor elements. If the difference is increasing one can conclude that one of the elements is drifting and the transmitter should be replaced. Another advantage with this sort of transmitters is that if one of the sensor elements fails there is an automatic switchover to the other sensor element so that no data is lost. Damages that can be monitored and detected are:

- Cable breakage.
- Short circuits.
- Poor insulation.
- Aging (drift).

If any of these damages occur, there is an automatic warning sent from the transmitter to the operator with information about what is wrong and that the transmitter should be replaced.

Using this kind of transmitters for monitoring machine health would mean that the measured values would be more reliable compared to conventional sensors, which would make the whole CBM system more reliable. It would also mean that the sensors would not be replaced for new ones unless it was actually needed which would save both time and money. However they are very likely to be more expensive than conventional sensors.

5.7 CONCLUSIONS

Considering the fact that the SCMS is already installed in the A26 and that it is relatively easy to add new sensors to it and store measurement data, the recommendation is that KAB make use of it as much as possible with a PIS, starting with applying it on only a few of the most critical systems on board with e.g. vibration measurements. The monitoring system can thereafter be progressively extended to other systems as well.

Even though a fully automatic PIS is appealing, the best solution, both economically and practically, is probably to have a combination of a PIS and a round based system. A PIS should be used on the most critical items and the items that need to be monitored in almost real time, e.g. the level A checkups performed every day. For the less critical systems on which it is physically possible a round based system could be used. To determine exactly which systems should be monitored using a PIS or a round based system one have to look into each system in greater detail which is outside the scope of this project.

The analysis software that should be installed on the SCMS should be as automatic as possible with as little human interaction in the analysis process as possible. This means that the crew only has to be educated in how the software works and how to interpret suggested maintenance actions and other messages. This would lead to a more consistent system that will come to the same conclusion no matter who is operating since it is the same program analyzing all the time. However, such a program put high demands on the supplier of the program or the development team if the program is developed by KAB because a fault in the program could be devastating. Such a program could be very difficult to develop which means it could decrease the plausibility of an implementation. Maybe a good starting point could be to implement a simpler program with human interactions that could be developed to a more automatic system over time.

As mentioned in section 5.4.3 operating data or detailed machine parameters are needed for the analysis program to establish the expected values for different run modes. Since operating data is stored by the Swedish Armed Forces, KAB should try to establish a deal with them so that the data after a few missions can be acquired by KAB and used to extend the CBM system to other systems and improve the analysis software.

A CBM system on the A26 submarine would help KAB fulfill their goals of a TLS service. This makes a CBM system very desirable since a TLS service would make the A26 submarine more attractive to costumers and possibly generate higher income and benefits for KAB.

Self monitoring transmitters is something that is not exactly needed, however one need to be able to fully trust the data measured by the sensors in a CBM system. All decisions regarding maintenance in a CBM system are based on sensor values and if those are incorrect it may lead to disastrous failures. With self monitoring transmitters one can detect when a sensor is failing and replace it before anything goes wrong, and because of that they are strongly recommended.

6 CASE STUDY – SCANIA DIESEL ENGINE

The diesel engines are the key power equipments on a submarine. They charge the main batteries as well as propel the ship. This chapter describes a theoretical case study of what a CBM system could look like on a Scania diesel engine. The engine that has been investigated is a Scania diesel engine type D16M. This engine is not necessarily the engine that will be used in the A26 submarine, although Scania is one of the preferred suppliers at this point in time and the D16M engine is the type that KAB has in mind [16], which is why it is chosen for this case study. It is a 16 liter V8 marine diesel engine.

First is a description of what is already measured and monitored in the engine followed by suggestions of what should be monitored for a well working efficient CBM system. If the engine should be monitored with a PIS or a round based system is thereafter discussed followed by what needs to be added and considered to fulfill the suggested system.

6.1 WHAT IS MONITORED ALREADY?

In the engine there are already a few preinstalled sensors and transducers that makes continuous measurements. These sensors can, if applicable, be used in different ways in a CBM system. Even though some of the measurements may not be able to detect any faults by themselves they can be of great usage by giving the analysis program information concerning the working environment and run mode of the engine. The preinstalled sensors that come with the Scania engine are presented in Table 6.1 [17].

Table 6.1 Preinstalled sensors that come with the Scania engine (source: [17]).

Sensor	Details
Engine speed sensor 1	Measures engine speed
Engine speed sensor 2	Measures engine speed
Oil pressure sensor	Measures the absolute oil pressure
Oil pressure and temperature sensor	Combined pressure and temperature sensor that measures the pressure and temperature of the oil
Sensor for charge air pressure and temperature	Combined pressure and temperature sensor that measures the absolute pressure and temperature of the charge air to the cylinders
Coolant temperature sensor	Measures the coolant temperature in the cylinder block after the coolant has passed the combustion chamber
Fuel temperature sensor	Measures the fuel temperature
Coolant level monitor	Measures the coolant level and alerts the operator/driver if the coolant level is too low.

Besides the sensors that come with the engine there are sensors mounted outside the engine, placed by KAB, to monitor the working environment such as ambient temperature and humidity.

6.2 MONITORING SUGGESTIONS

6.2.1 OIL ANALYSIS

Based on the number of publications in the field, oil lubricant analysis seems to be the most commonly used and efficient way to monitor a diesel engine. It is a very convenient monitoring method since it can detect not only that something is about to go wrong (raised levels), but also what is wrong and sometimes even what the cause is. Oil lubricant monitoring does not only give indications regarding the oil quality and the suitability of continued use of the oil. By monitoring the oil one can detect contaminations and particles in the oil which is related to the degree of wear on moving parts in the engine itself [18] e.g. bearings, pistons, piston rings, valves etc. In other words, oil lubricant monitoring can detect both degraded oil quality as well as wear on moving engine parts [19, 20].

When analyzing the oil lubricant one can check for different kinds of elements and particles simultaneously. Basically all kinds of elements can be detected and by analyzing the trend curves for the different element concentrations one can determine which part of the engine is wearing down and/or is damaged[19]. For example, if silicon (Si), Iron (Fe) and lead (Pb) has elevating trend curves one can draw the conclusion that there is dirt in the system because of the detection of rising silicon levels. A probable cause for dirt in the engine is that an air filter is somehow failing. The elevated levels of iron and lead show that pistons, cylinders and crankshaft have begun to wear because of the dirt. Without oil analysis one would in this case only detect wear on the engine parts (e.g. with vibration measurements) and they would be replaced. The cause of the wear, i.e. the dirt in the engine, would not be detected and thus the newly replaced parts would soon get worn down as well [19]. For more similar examples and oil analysis cases *Condition Based Maintenance System for Heavy Equipments Case study: Using Trend Analysis in Oil Monitoring* [19] is recommended.

The four most common “engine killers” for general diesel engines (i.e. not Scania engines in particular) are [20]:

1. **Dirt in the system**
   Dirt in the system acts as an abrasive and can quickly wear down the moving parts in the engine. If there is dirt in the engine there will also be dirt in the oil lubricant which can be identified by the detection of aluminum and silicon. If other elements such as iron and chromium is also detected, one can draw the conclusion that engine parts such as pistons and piston rings has begun to wear down by the dirt.

2. **Fuel dilution of the oil**
   Not all fuel injected to the cylinder in a diesel engine is expended during the combustion process and some of the unburnt fuel will inevitably work its way past the piston into the crankcase. The fuel will there mix with the oil lubricant, which changes the viscosity and lubricity of the oil which can eventually cause wear on basically all moving parts of the engine. Fuel dilution of the oil lubricant can be identified by the detection of a change in the oil viscosity.

3. **Soot**
   In all combustions engines soot particles will inevitably form during the combustion process. These soot particles will get mixed up with the oil lubricant and if not adequately dispersed within the oil they will agglomerate and increase the oil viscosity. If the oil viscosity gets too high it can lead to plugged filters and lubrication starvation, leading to metal on metal contact and wear. Agglomerated soot particles can also act as an abrasive and wear down the moving parts in the engine much like dirt in the system.

4. **Coolant leakage**
   If there is a coolant leakage into the oil flow the coolant will eventually work as an abrasive on the softer metals in the engine such as the copper and lead in bearings. Coolant in the oil is identified by detecting sodium and/or potassium.

Another great advantage with oil analysis is that it is not dependent on the submarine's working environment such as water temperature, humidity, pressure, salt concentration etc. if the oil is contaminated with some sort of particles, the particle concentration will not be affected by the environment in the same way as e.g. vibrations would.

6.2.2 VIBRATIONS

Even though oil analyzes are very efficient and can detect a lot of different errors and causes, there are some that they cannot detect. For example if there is an alignment error between two axes the bearings would wear down. Oil analysis would detect the wear but it could never detect why the bearings were wearing down. Vibration monitoring however could do that, and do so even before the bearings would wear down, which would be a great advantage. For this case vibration measurements could detect:

- Misalignments (e.g. of engine and generator)
- Wear
- Cylinders not firing
- Bearing problems
- Parts not tightened enough or not mounted correctly
- etc.

For other examples of what errors vibration monitoring can detect and what advantages this kind of monitoring has, see section 4.6.1.

Vibration monitoring in combination with oil analysis should be able to detect most kinds of failures that may occur in a diesel engine and should be able to pin point the exact causes.

6.2.3 OTHER

Besides Oil monitoring and vibration monitoring there should also be measurements of the environment and work mode of the engine as input to the analysis program. Without inputs like that it can be very difficult to establish expected values for i.e. vibrations, and maintenance actions may be hard to plan. Such measurements are however already made, as mentioned in section 6.1.

6.3 CHOICE OF MAINTENANCE SYSTEM (PIS OR ROUND BASED?)

To take full advantage of all the benefits with CBM and to reduce the work load of the crew as much as possible a PIS is recommended. However, a fully autonomous CBM system as described in section 4.4 might be extremely difficult to implement and realize due to the complicated correlations between all the different trend curve reactions to different machine errors. Thus, to increase the plausibility of a future implementation, a good starting point is probably to have a PIS connected to the SCMS with a simpler analysis program. Trend curves of all the monitored data should be created and the analysis program should be able to detect abnormalities and changes in the trend curves and give the operator a warning should something be abnormal. When a warning is issued a knowledgeable technician can analyze the trend curves and the correlations between them and determine what is wrong and what the cause is. The technician could then be able to determine what maintenance action should be performed and when it should be performed.

6.4 WHAT NEEDS TO BE ADDED?

To be able to perform on-line monitoring of the oil and vibrations of the engine in near real time, sensors capable of doing that need to be bought and installed. There are numbers of companies specialized in the field which provides both different kinds of oil monitoring sensors as well as vibration sensors.

Besides sensors, an analysis program needs to be developed and installed in the SCMS. Since it for starters should be a relative simple program that only alerts and issues alarms if something seems amiss and does not involve too complicated predictive algorithms, it could probably be developed internally by KAB. However, if the program is not fully autonomous a technician specialist is needed, or someone has to be trained to analyze the trend curves to make accurate estimations of the machine health.

6.5 CONCLUSIONS

The sensors that are already installed in the engine can be used to give important information to the analysis program, however they cannot be used to pinpoint potential faults in the machine. For that oil analysis combined with vibration monitoring is suggested. This combination should be able to detect most, if not all, faults and pinpoint what is wrong.

To increase the plausibility of an implementation a simpler system should initially be implemented, with an analysis program that can alert a specialized technician when something is wrong. The technician can then analyze the trend curves further and determine what the fault is. The program can then be progressively developed and improved to be more automatic.

7 FURTHER RESEARCH

7.1 CBM ON A26

7.1.1 SYSTEMS IN THE CBM PROGRAM

Which systems that should be part of the CBM system need to be investigated. This can be done by looking into each system in detail much like what is done in the case study in chapter 0. By doing this one can determine whether or not each system is suitable to be part of the CBM program, what kind of measurements are required for each system and what kind of CBM system is best suited for each system.

7.1.2 ANALYSIS PROGRAM

One has to investigate whether an analysis program should be developed internally at KAB or if it should be bought from an external supplier. One has to consider what exists on the market today, what the costs for such programs are, and what the costs of developing such a program internally would be.

Another thing that has to be decided regarding the analysis program is how it should be able to estimate expected values and critical levels for the systems depending on run mode and working environment etc. Should it be based on an ANN or a model based on machine parameters?

7.1.3 MAINTENANCE PLAN

One should look at the existing maintenance plan and investigate which maintenance tasks that can be affected by a CBM system. With that information one could determine how much of the maintenance in total that will be affected and it might be possible to estimate how much the maintenance can be made better and how much more availability could be achieved.

7.1.4 COSTS

Lastly one should investigate what the costs of the desired CBM system would be. Depending on what the costs are and what it would achieve regarding an increase in safety and availability of the submarine, is it worth it? What is the extra availability allowed to cost for it to be beneficial?

7.2 CASE STUDY – SCANIA DIESEL ENGINE

7.2.1 NEW SENSORS

If oil analysis and vibration monitoring are to be used one has to investigate which sensors should be bought and what is available on the market. The sensors have to be reliable, cost effective and most importantly they have to be compatible with the SCMS.

7.2.2 SENSOR PLACEMENT

If new sensors are to be installed one has to determine exactly where on the engine the sensors should be placed to be most beneficial. If a vibration sensor is improperly placed it might not be able to detect some of the potential faults. One also has to investigate how many sensors are needed. One vibration sensor might not be enough to monitor the vibrations of the whole engine.

7.2.3 ANALYSIS PROGRAM

As mentioned in section 7.1.2 the analysis program and how to establish expected values and critical levels needs to be investigated for all systems intended to be part of the CBM system. What are the expected values and critical levels of oil contaminants and vibrations for a Scania diesel engine with the run modes used on a submarine?

7.2.4 MAINTENANCE PLAN

One should look at how the maintenance of the diesel engines could change. As mentioned in section 5.1 there might be a problem with how much one could change the suggested maintenance plan regarding the warranty from the supplier. If one does not follow the suggested maintenance plan the warranty might not apply.

7.2.5 COSTS

Finally, to be able to calculate the total costs for the whole CBM system on the ship (as mentioned in section 7.1.4) one need to know the costs for each system. Therefore it is needed to calculate the development and investment costs for the CBM system on the diesel engines. When the costs are approximated it is also needed to decide if the CBM system is beneficial for the diesel engines.

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